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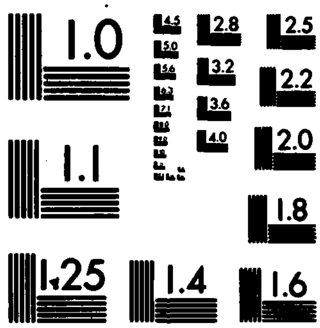

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Final Report

May 1979

CHEMICAL PHYSICS OF CHARGE MECHANISMS IN NONMETALLIC SPACECRAFT MATERIALS

By: R. C. ADAMO J. E. NANEVICZ

Prepared for:

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The results of the materials charging behavior studies provide an empirical measure of some of the complexities of materials behavior under dynamic conditions more typical of those encountered in space than are normally used in ground-based simulations and indicate that many present laboratory simulation and measurement techniques may not provide data truly representative of actual in-orbit spacecraft charging effects.

The results of the discharge characterization experiments indicate that electromagnetic transients caused by sample discharges produced signals in external sensors indicative of transient electric field changes of tens of kV/m at locations several inches from the sample boundaries. The magnitudes of these external fields are comparable to those associated with nuclear electromagnetic pulse (EMP) events and can produce high-level transient signals in spacecraft electronic systems. These transient electromagnetic signals can therefore be considered as extremely energetic sources of possible electromagnetic interference on spacecraft.

SRI International

Final Report *May 1979*

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I INTRODUCTION

The interactions of spacecraft and space systems with the changing solar illumination and charged-particle environments in the vacuum of space result in the occurrence of a number of electrostatic and electromagnetic phenomena. These phenomena, commonly referred to collectively as spacecraft charging effects, can produce undesirable and sometimes serious problems with the performance and operation of military, commercial, and NASA spacecraft.

In order to further understand and eventually reduce or eliminate this spacecraft charging problem for present and future satellites and space structures, a cooperative NASA/Air Force program was initiated in 1975. The objective of this spacecraft charging investigation is to provide design criteria, materials, construction techniques, and analytical test methods to ensure control of the absolute and differential charging of spacecraft surfaces.

This information is of particular importance to the Air Force, since many present and planned Air Force operational satellites, as well as larger space structures, will occupy geosynchronous orbit altitudes where spacecraft charging problems appear to be most severe. The intelligent development of new materials and design practices to ensure the high reliabilty and long lifetime of future space systems requires a practical understanding of spacecraft charging phenomena and their effects.

The laboratory program described in this report was performed by SRI International under contract to the Air Force Office of Scientific Research (AFOSR) to explore the behavior of typical polymeric spacecraft surface materials under simulated orbital conditions to provide a better understanding of the electrostatic and electromagnetic charging and discharging processes associated with spacecraft charging phenomena.

A. Background

External surfaces of objects in space are exposed to continually changing charged-particle and solar-illumination environments. The instantaneous electrostatic potential of any particular portion of an object's surface is determined by the exact nature of the local environment and by the physical and electrical characteristics of the combination of materials of which the surface is comprised. Due to differences in such properties as secondary emission, backscatter, photoemission, and conductivity, it is possible for large differences in potential to exist between electrically isolated portions of materials at or near an object's surface.

During the past few years, analytical studies as well as laboratory simulation experiments and in-flight measurements have shown that, under certain conditions, particularly at or near geosynchronous orbit altitudes, the electrostatic potentials of surface materials commonly used on space vehicles can reach levels of several thousand volts. The electric fields resulting from these differences in potential can interfere with the performance of on-board scientific measurements and can cause the reattraction and deposition of contaminants on critical surface materials. In addition, if the potential differences between portions of surfaces are large, electrical discharges can occur. Such discharges can produce electrical noise in on-board electronic circuits resulting in anomalous behavior of critical systems and can cause physical damage to surface materials and the liberation of electrically-charged contaminants.

The recognition of spacecraft charging as a threat to the reliability of spacecraft operation has stimulated a considerable amount of work in several areas and involving several disciplines. Perhaps the greatest progress has been made in the areas of modeling of the geosynchronous charged-particle environment and computer simulation of the gross features of the interaction of that environment with spacecraft.

In addition, in late January, 1979 the P78-2 spacecraft was successfully launched. A significant portion of the P78-2 payload is designed to provide a considerable amount of information about the detailed nature of

the in-orbit charged-particle environment.[1*] Several additional instruments on P78-2 are designed to simultaneously characterize certain features of the behavior of spacecraft systems and materials in the measured environment.

Unfortunately, even in laboratory simulation experiments in which the charged-particle environment is relatively simple as compared to that found in space, the behavior of many commonly used spacecraft materials is quite complex. Internal and external charge-storage and breakdown properties of many materials are affected by material time constants, inhomogeneous internal conductivity profiles, and complex interactions between fields, charged particles and solar illumination. Although progress is being made, at present there is a lack of understanding of the fundamental basis for the electromagnetic behavior of such materials.

Further complications arise on operational spacecraft because multi-layer materials are often used, many different materials are frequenctly arranged in complex geometries, and the energy spectrum of the charged-particle environment is continually changing.

The results of the empirical measurements on the P78-2 spacecraft should prove extremely valuable in that they will provide insights into material behavior under actual in-orbit conditions and will allow the adequacy of ongoing and future laboratory and computer simulation studies to be evaluated and improved.

In light of the present state of knowledge and the information that is expected to be obtained from the P78-2 spacecraft during the next year, several important questions regarding spacecraft charging phenomena remain unanswered.

In the area of materials behavior in space, laboratory measurements of external fields and back surface currents for isolated materials, as well as for actual functional thermal-control and solar cell materials, have been made using monoenergetic electron sources and solar simulators. Much of the original work on the effects of solar illumination on material conductivity

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* References are given at the end of this report.

properties was performed by SRI International under contract to NASA Lewis Research Center.[2] In addition, preliminary measurements of such basic parameters as the photoemission, secondary emission, and backscatter properties of some materials have been made, and additional detailed studies of some of these parameters are planned for the near future.

Several questions as yet unanswered involve differences in the observed behavior of certain materials and the reasons for these differences. For example, the bulk conductivity of Kapton is increased considerably by constant solar illumination and remains so for long periods after the source of illumination is removed.[2] The bulk conductivity of Teflon increases relatively slightly under illumination and returns to its initial value rapidly in the dark.

A more complete understanding of the differences in the behavior of these materials under conditions representative of those encountered in space would aid in the selection of appropriate materials for particular space applications and could lead to the development of new functional materials having more desirable charge control properties.

The nature of elecrical discharges produced by spacecraft charging phenomena is also of great concern for operational space systems. As stated above, in addition to causing materials damage and the liberation of contaminating materials, electrical breakdowns produce transient electromagnetic signals that can couple into on-board electronic circuitry resulting in unexpected satellite system behavior or damage.

In 1974, a set of instruments designed by SRI to detect the occurrence of electrical discharges was flown on a synchronous orbit satellite.[3,4] A simple analysis of the data obtained from these instruments has shown that electrical discharges did occur on surfaces of the satellite, spin synchronous discharges occurred at a low rate (approximately 30 per hour) throughout the orbit, non-spin synchronous discharges occurred at a much higher rate (approximately 10 per minute) during geomagnetically active periods near local midnight, and the occurrence of certain troublesome on-board electrical anomalies could be directly correlated with the occurrence of discharges on the satellite's surface.

Electrical discharge monitoring instruments designed and built both by SRI and by the Aerospace Corporation are being flown on the P78-2 spacecraft. These instruments can detect and characterize electrical transients on spacecraft systems. However, because of the complexity of the coupling paths between the fields and currents produced at the locations of external discharges, and the electrical response of spacecraft circuitry, it is unlikely that the exact locations and electromagnetic characteristics of discharges on P78-2 will be derivable from the data obtained.

Information regarding the nature of the electromagnetic noise as it is generated at the source is essential for the design of cost-effective space systems having the required immunity to discharge transients.

B. Scope of This Report

Section II of this report describes the experimental apparatus and test procedures, as well as the results of tests performed by SRI International under contract to AFOSR, to further define the charging and discharging characteristics of typical spacecraft polymeric materials under orbital charging conditions. Section III presents conclusions based on the results of this work and some recommendations for future efforts.

Specifically, Sections II A and B describe tests and test results concerning the laboratory behavior of Kapton and Teflon films under dynamic charging conditions.

Sections II C and D describe preliminary laboratory tests to determine the electromagnetic characteristics of discharges on silvered quartz OSRs and Teflon films. The results of this work indicate that such discharges represent a severe potential electromagnetic threat to space systems. Partially as a result of this study, the initial phases of a more complete program for the characterization of discharge-induced electromagnetic transients have begun. The scope of this follow-on program being funded by SAMSO, and recommendations for future efforts in this area, are described in Section III.

II EXPERIMENTAL TESTS AND TEST RESULTS

The laboratory experiments performed for this program can be conveniently categorized into two separate but related areas: the study of material charging behavior and the study of the characteristics of electrical breakdowns on spacecraft materials.

The performance of the materials charging behavior tests was motivated by observations of the responses of commonly used spacecraft materials under conditions more typical of those encountered in space than have normally been used for laboratory simulation tests.

For example, in many laboratory tests, Kapton or Teflon samples have been exposed to monoenergetic electron beams while back-surface bulk currents and external electric fields were monitored in the dark or, in some cases, under constant simulated solar illumination. Steady state tests of this type are useful for the determination of certain fundamental material parameters. However, the occurrence of electrical discharges in synchronism with the several-rpm vehicle spin rate (as detected by SRI instrumentation on an in-orbit geostationary satellite[3,4]), as well as observations made during the performance of steady-state laboratory materials behavior tests at SRI International, strongly suggest that dynamic processes may be of critical importance to the understanding of certain spacecraft charging-induced problems on operational vehicles.

For this reason, a series of tests was conducted in which material bulk currents and external electric fields were monitored during exposure to electron beams of various energies both in the dark and under conditions simulating the modulated solar illumination encountered on spin-stabilized operational spacecraft. The laboratory setup used for the materials charging tests and the test results are described in Sections II A and B of this report.

During the performance of laboratory simulation tests of spacecraft charging phenomena, electrostatic discharges are frequently produced on test samples, particularly at higher electron beam energies and current densities. The actual occurrence of electrical discharges on spacecraft surface materials has been confirmed by on-orbit measurements, and it is these discharges that are the most likely cause of many spacecraft charging-induced vehicle anomalies.

An understanding of the electromagnetic characteristics of surface material electrical discharges is, therefore, necessary for the intelligent design of electronic space systems immune to their effects.

In many spacecraft materials charging studies, attempts have been made to characterize the magnitude of electrical signals produced by discharges by monitoring the "return current" that flows through a "short-circuit" connection between the conductive back surface of the test sample and the test chamber system electrical ground. With this test setup, currents flowing as a result of charge redistribution between portions of the test samples and the sample back surface do not produce a direct injection of current in the "return current" monitoring circuitry. Measured "return currents" are produced by charge "blow-off" currents flowing between the test sample and the test chamber walls and by electromagnetic field coupling between the total charge redistribution current flow and the "return current" measurement circuitry.

Simple "return current" measurements, therefore, provide only a second-order measure of the actual characteristics of charge redistribution current flow and the resulting electric and magnetic fields, and are critically dependent upon the electromagnetic features of the overall test facility. For these reasons, modifications were made to the materials charging test setup to allow a better measure of the basic electromagnetic characteristics of sample breakdowns to be obtained.

A description of these discharge characterization tests and their results are contained in Sections II C and D.

A. Materials Behavior Test Setup

The materials behavior tests described in this report were performed in a metal vacuum chamber 30 in. in diameter by 36 in. high, fitted to the top of a 16-in. NRC oil-diffusion pump equipped with a liquid nitrogen cryogenic baffle and a 16-in. gate valve. This chamber can attain a vacuum of the order of 10^{-6} torr with sizable outgassing loads so that tests may proceed with a minimum delay due to system pumpdown. The chamber is equipped with a 9-in. dia. viewing window and numerous ports for mechanical and electrical feedthroughs.

The test setup also includes an electron gun and a xenon lamp solar simulator. The electron gun is of a special type designed at SRI and uses a multipactor electron source to provide a large-area uniform beam over a wide range of energies and current densities.[5] The electron-gun circuitry includes a sensitive feedback system to maintain the electron-beam current density at a preset level over long periods of time. This feature was valuable for this program because it allowed the system to reliably operate for periods of many hours during long-term tests.

The xenon lamp used in these tests is a sealed-beam unit with an aluminum reflector and a sapphire window to enhance the output in the ultraviolet and infrared portions of the spectrum. The xenon lamp was mounted outside the vacuum chamber and samples were illuminated through a 6-in. dia. fused quartz window mounted in the chamber wall.

In all tests in which illumination was required, the xenon lamp was used to produce an optical power density equal to one solar constant (approximately 140 mW/cm^2) at the sample surface with 99.8% of the lamp output power in the 200-to-2100-nm wavelength range. The test samples were shielded from illumination, as required, using an opaque shutter assembly that totally prevented light from the illuminator from entering the vacuum chamber. In addition, during illuminated tests, a circular iris was used to restrict illumination to the front surface of the sample materials and thereby prevent photoelectron emission from other surfaces within the test chamber. A highly regulated (0.025%) 20-kV power supply was used to supply

accelerating voltages for the electron gun. All current measurements were made using HP425A picoammeters having a minimum current resolution of approximately 10^{-12}A. In order to approximate the variations of solar illumination that normally occur on spin-stabilized spacecraft, modulation of the xenon light source was produced using a variable-speed rotating mechanical chopper with a 50% duty cycle. This arrangement provides a reasonable simulation of actual in-orbit illumination conditions, although the angular variations and complex shadowing conditions normally encountered on spin-stabilized spacecraft could produce additional effects.

The basic setup used for the materials charging behavior tests is illustrated schematically in Figure 1. For these tests, circular Kapton and Teflon test samples were prepared by sputtering gold electrodes on the back side of the sample material. The outer annular gold electrode was used as a guard electrode and the center gold electrode was used to monitor the sample bulk current. The area of the center gold electrode was 7.07 cm^2 with a 1.5-mm gap between the center and guard electrodes. The test samples were held in place on the sample mounting plate by means of a grounded brass ring.

In order to measure the potential of the test samples, an electric-field monitor was included in the test setup. This device was mounted near the test sample holder as shown in Figure 1. The relationship between the electric field measured at the detector and the potential of the sample was determined by installing a thin, electrically-isolated conductive plate in place of the sample in the sample holder. By applying various voltages to the conductive plate, the linear relationship between electric field and sample potential was established for the particular geometry and spacing of the test setup.

Virtually all true electrostatic-field measuring devices incorporate a mechanical chopper to cover and uncover a conductive sensor electrode. The magnitudes of transient currents induced in this electrode, as it is alternately shielded from and exposed to an external electric field, are then used to determine the magnitude and polarity of that field. It should be noted, however, that an electric-field monitor mounted as shown in Figure 1

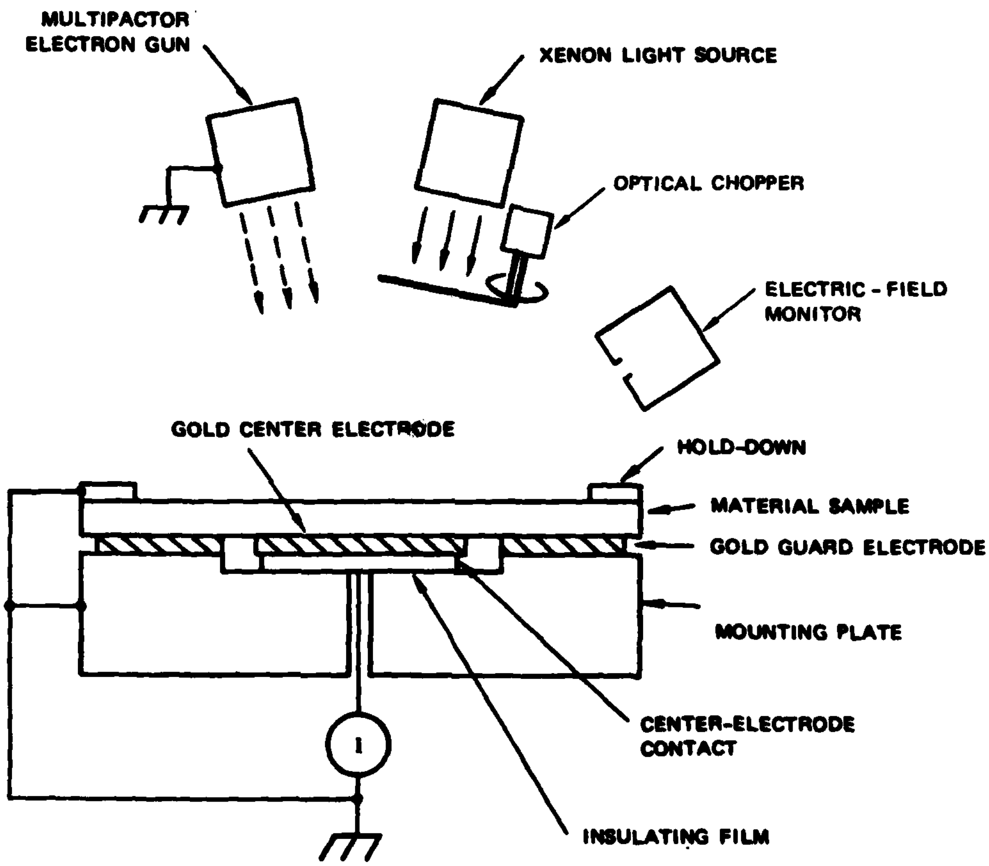


FIGURE 1 SETUP FOR MATERIALS CHARGING TESTS

is exposed not only to external electric fields but also to the charged-particle and illumination environments present in the test chamber.

Conventional electrostatic-field measuring instruments designed for use on the ground or in the lower atmosphere will frequently produce erroneous readings in such an environment since they are unable to distinguish between signals induced by true electric fields and those produced by charged particles flowing to, or photoemission from, the sensor electrodes.

The electrostatic-field monitor used for the materials charging tests was designed and constructed by SRI International and was modified to allow true electric-field measurements to be accurately made in a charged-particle and solar-illumination environment. The specially designed input circuitry and signal processing electronics enable true electric fields to be measured in the presence of currents produced by charged particles or photoemission and, in addition, provide separate independent outputs indicating the magnitudes and polarities of both the electric fields and the total convection currents.

Prior to the start of the materials charging studies, the functioning of the modified electric-field monitor was thoroughly tested in the chamber environment. For these tests, the monitor was mounted so that it could be exposed directly to both the solar simulator and the electron beam. A metal plate was also mounted in the chamber and connected to a voltage source to produce a true static electric field. The response of the electric-field monitor to this field was first determined in the absence of other stimuli. This test was then repeated with the solar simulator turned on, with the electron gun turned on to produce beams of various current densities and energies, and with both devices on simultaneously. Even under the most severe test conditions, with the electric-field monitor directly exposed to one solar constant of illumination and electron beam current densities of tens of nA/cm^2, the true electric field was accurately measurable to within a few percent.

The electric-field monitor is a compact device requiring less than 1 W of power for continuous operation. The results of these tests indicate that it is not only well suited for vacuum chamber spacecraft charging simulation

studies, but could also be readily modified for use as an external field monitor on operational spacecraft.

B. Materials Behavior Test Results

The materials behavior tests discussed in this section were performed using the test setup just described and shown in Figure 1. Several series of similar tests were performed on both Kapton and Teflon samples in order to compare the charging behavior of these materials.

Initial tests of Kapton and Teflon samples conducted totally in the dark reconfirmed that in the absence of illumination these materials behave relatively similarly under a given set of electron-beam conditions, and that their bulk currents, charging time constants, and steady-state external fields are of comparable magnitudes.

However, in all tests conducted under modulated illumination, Kapton and Teflon behaved quite differently. For example, Figure 2 illustrates the bulk-current waveforms measured in 5-mil Teflon and Kapton samples during exposure to a 10 keV, 5 nA/cm^2 electron beam and, simultaneously, to illumination having equal on and off periods of 30 s to approximate the possible illumination conditions on a 1-rpm spin-stabilized spacecraft. It is readily seen that under these test conditions the bulk currents in Teflon and Kapton differ greatly in magnitude during the dark portions of each cycle and differ not only in magnitude but in polarity during the illuminated portion of each cycle. During these particular tests, the electron beam remained on for a 1-h period. No significant changes in the measured currents occurred during this time.

After 1 h of electron-beam exposure, the electron gun was turned off. Figure 3 illustrates the bulk currents measured approximately 15 min after gun turn-off. For the period shown, during the dark portion of each cycle the measured currents in both materials are relatively low. However, during the illuminated portion, the Kapton sample produces a negative peak current of a few pA, while the Teflon sample produces a positive peak current of tens of pA.

Figure 4 illustrates the results of bulk-current measurements performed under conditions similar to those for Figure 2, but with an electron-

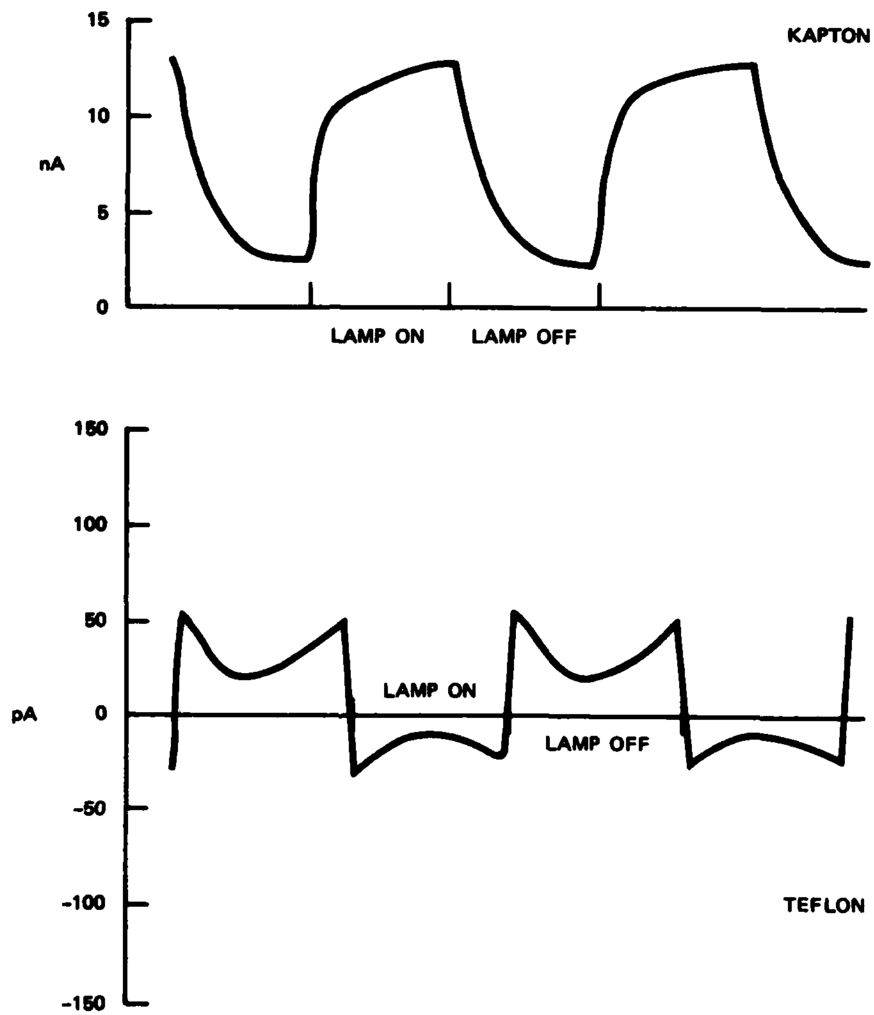


FIGURE 2 BULK CURRENTS IN TEFLON AND KAPTON SAMPLES DURING EXPOSURE TO 10 keV, 5 nA/cm^2 ELECTRONS

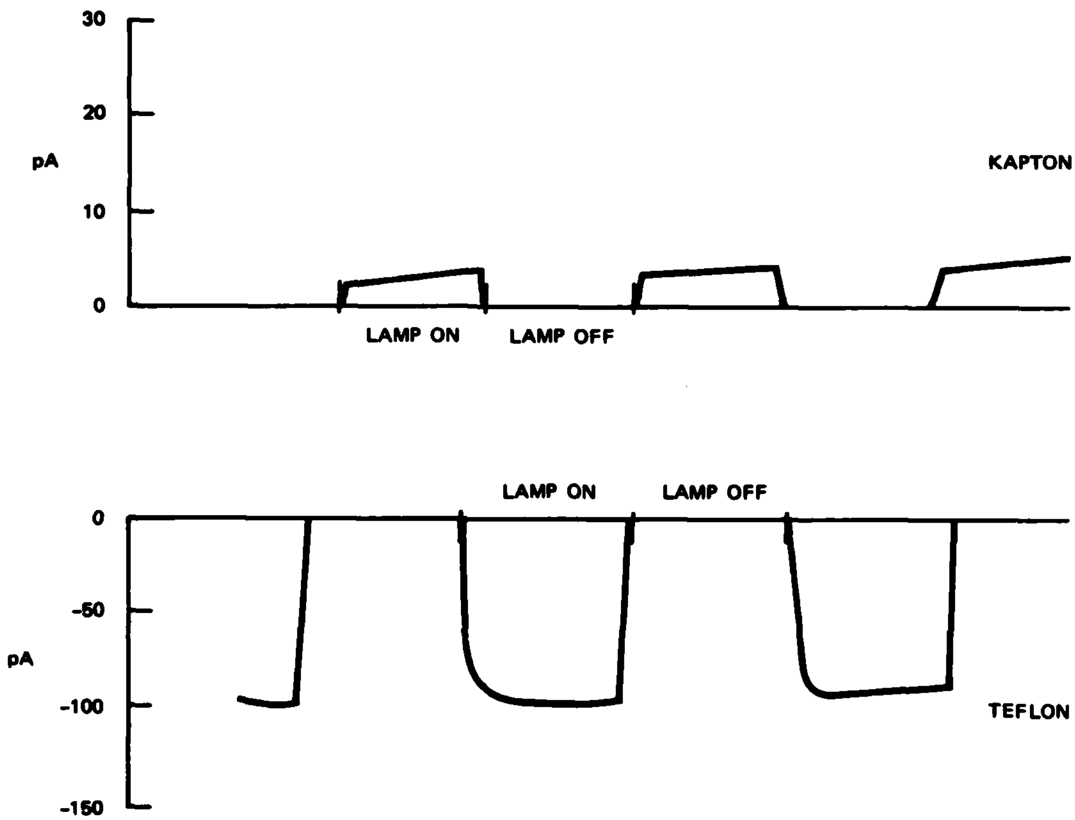


FIGURE 3 BULK CURRENTS IN TEFLON AND KAPTON SAMPLES AFTER EXPOSURE TO 10 keV, 5 nA/cm^2 ELECTRONS

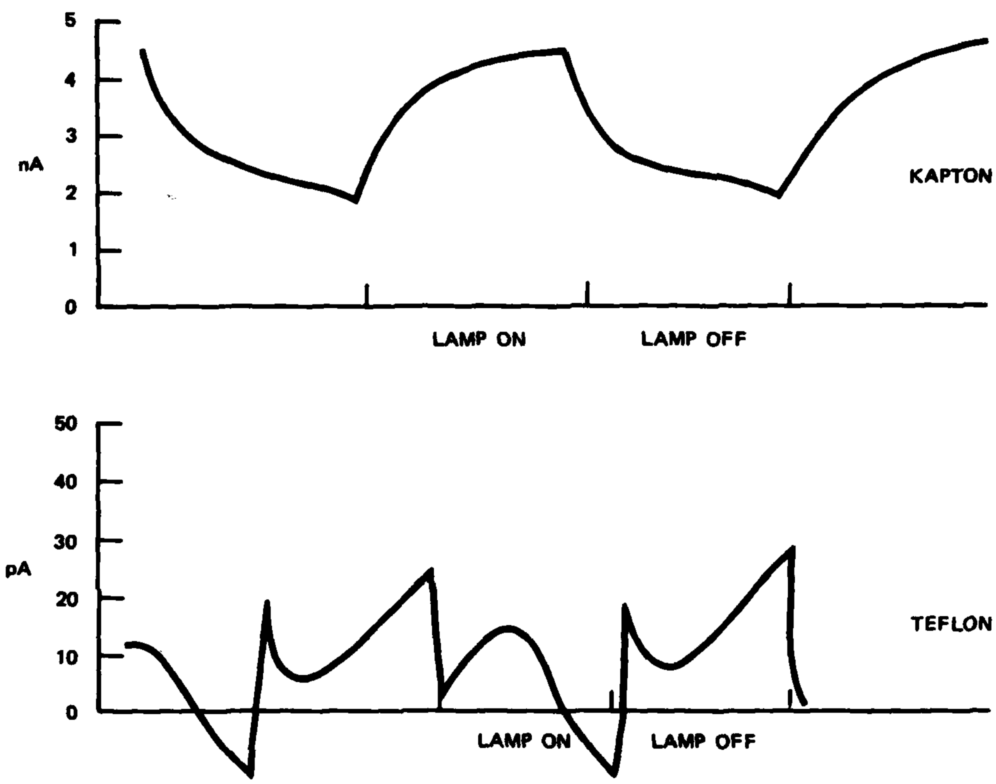


FIGURE 4 BULK CURRENTS IN TEFLON AND KAPTON SAMPLES DURING EXPOSURE TO 5 keV, 5 nA/cm^2 ELECTRONS

beam energy of 5 keV. The bulk currents in the Kapton sample are similar to those measured at 10 keV but have a somewhat lower peak magnitude during the illuminated portion of each cycle. The currents in the Teflon sample, however, have reversed polarity as compared to those measured with a 10 keV beam, in that they are negative at the end of the illuminated portion and positive during the dark portion of each cycle. After the 5-keV electron beam was turned off, both Kapton and Teflon currents were similar to those shown in Figure 3 for the 10-keV tests.

Figure 5 shows the equivalent Kapton and Teflon surface potentials, as measured by the electric-field monitor during the same test period and under the same test conditions as for Figure 2. This figure illustrates another major observed difference between the behavior of Kapton and Teflon. The measured potential of the Teflon sample remained relatively constant with only minor periodic variations at the simulated spin rate. These values remained virtually unchanged during 1 h of exposure to both electrons and illumination.

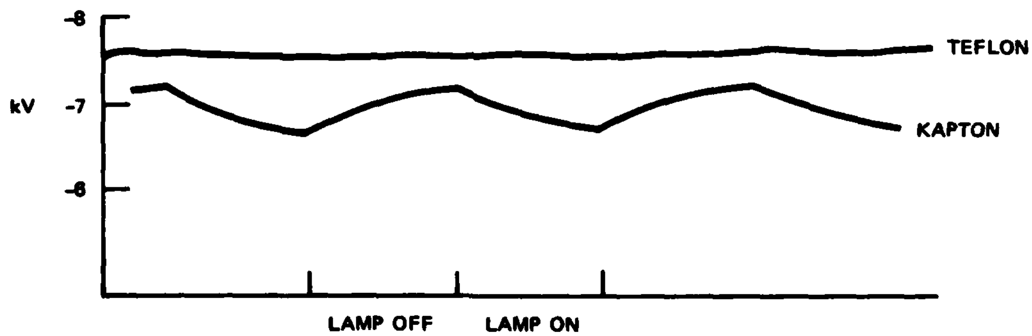


FIGURE 5 POTENTIALS OF TEFLON AND KAPTON SAMPLES DURING EXPOSURE TO 10 keV, 5 nA/cm^2 ELECTRONS

The Kapton sample, on the other hand, shows large fluctuations at the simulated spin rate. An additional difference, illustrated more clearly later in this section, is that the overall Kapton surface potential is decreased markedly during the 1-h exposure to both the electron beam and the

modulated solar simulator. This decrease in average potential with time under illumination is most likely due to previously observed long-term changes in Kapton bulk conductivity.[2]

Figures 6 and 7 summarize the data obtained during the overall test sequences for Teflon and Kapton during which the data shown in Figures 2 through 5 were obtained. These figures again illustrate the large periodic variations and the overall decay of potential that occurs with Kapton, but not with Teflon, during the electron beam exposure period. It can also be seen that the overall Kapton potential decays quite rapidly after the electron beam is turned off, while the Teflon potential decays much more slowly.

Data were also obtained under similar test conditions but with simulated spin rates from 0.5 to 10 rpm. In these tests, the range of potential variations during each illumination cycle decreased as the spin rate was increased. However, as in the tests described above, the potential of Teflon averaged over many cycles remained essentially constant during electron beam exposure and decayed relatively slowly after the beam was turned off. For Kapton, the average potential decayed at approximately the same rate as shown in Figure 7, both during and after electron-beam exposure over the entire range of spin rates. For test periods that are long compared to the spin period, the total time of exposure to illumination is equal to one-half the test duration, regardless of the spin rate. The average decay in Kapton potential, therefore, again appears to be related to the total duration of exposure to illumination.

Similar differences in behavior between Kapton and Teflon were seen at all electron beam energies above approximately 3 keV. Only a limited number of short-term tests were performed with beam energies below 3 keV. In this energy range, the secondary emission properties of the test materials have more significant effects and lesser amplitude but more complex differences in surface potential and bulk-current behavior between Kapton and Teflon were observed.

Some implications of the results of these materials behavior tests, as well as suggestions for future work in this area, are discussed in Section III.

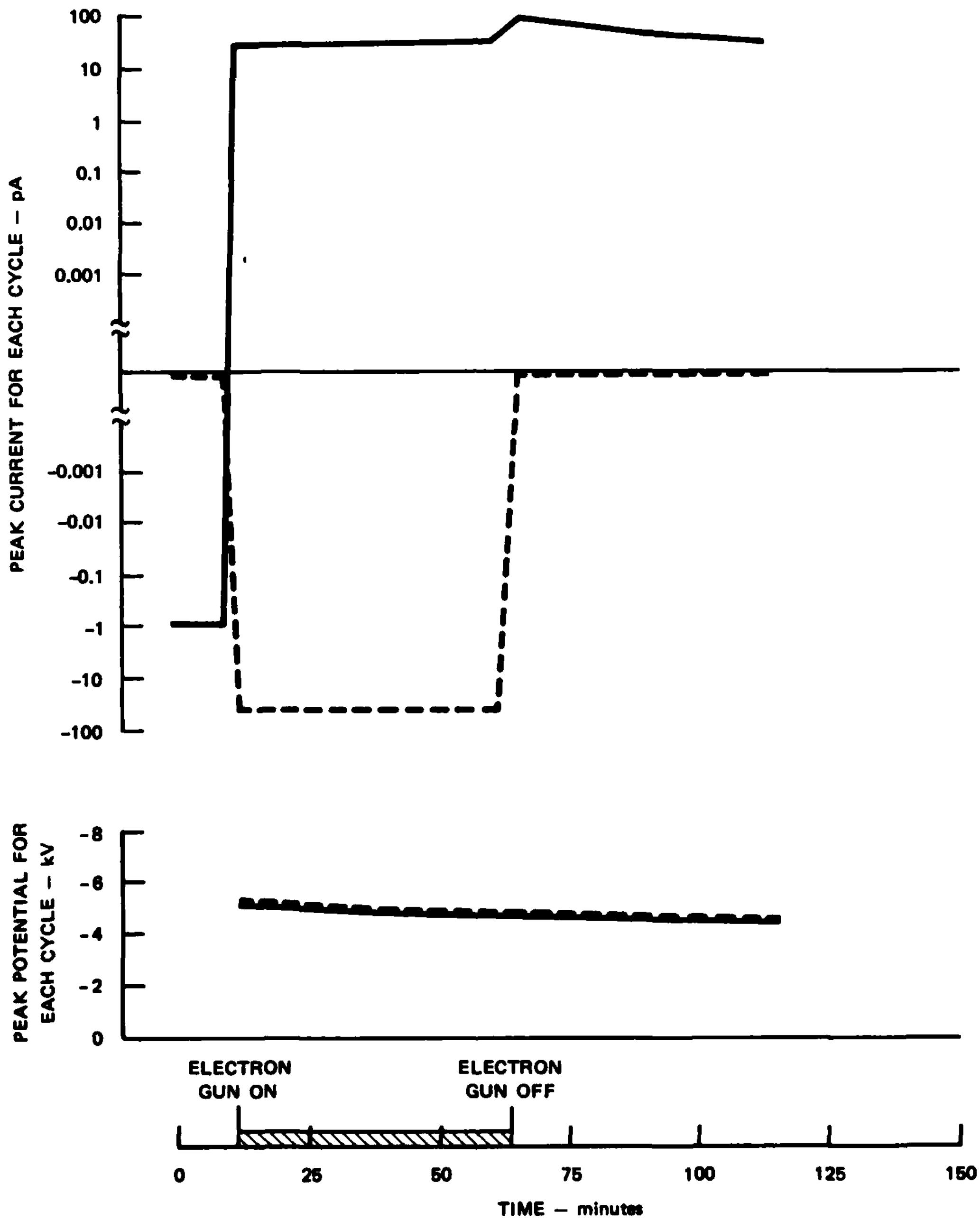


FIGURE 6 SUMMARY OF TEFLON TESTS WITH 10 keV ELECTRONS

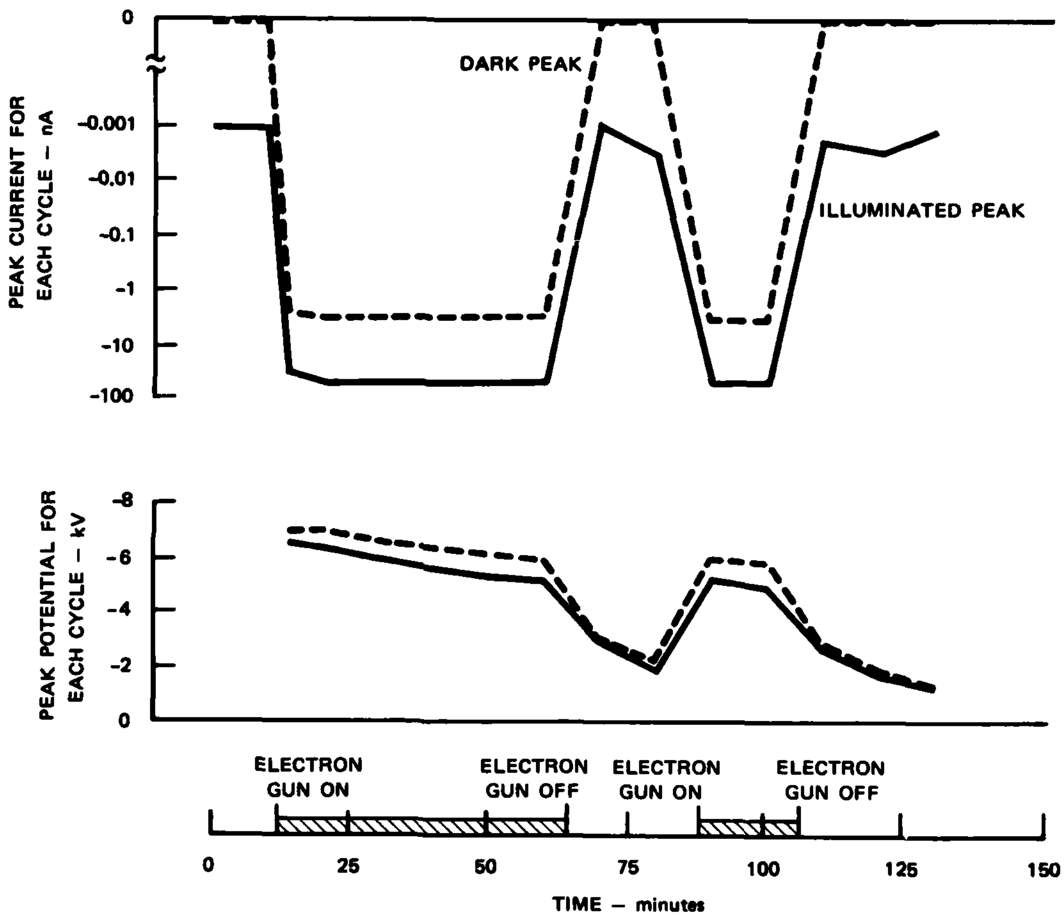


FIGURE 7 SUMMARY OF KAPTON TESTS WITH 10 keV ELECTRONS

C. Discharge Characterization Test Setup

As is discussed in Section I A, "return current" transient measurements are not directly useful for the definition of the electromagnetic characteristics of signals generated by electrical breakdown of spacecraft materials. For this reason, the test setup used for the materials behavior studies was modified to allow a more direct measure of electromagnetic discharge characteristics to be made. For these tests, the sample holder shown in Figure 1 was replaced by a larger area grounded conductive plate on which material samples could be mounted.

Electromagnetic transient measurements were performed in this setup using a loop antenna and associated instrumentation as shown in Figure 8. The loop antenna consisted of an uninsulated rigid wire firmly attached to the ground plane at both ends. Current in the loop antennas was measured using a Tektronix CT-1 current probe and a Tektronix 7844 oscilloscope. The current probe, when operated into a 50-ohm load, has a sensitivity of 0.2 mV/mA and a 3-dB bandwidth from 35 kHz to 1 GHz. The Tektronix 7844 oscilloscope, equipped with 7A19 vertical amplifiers, provides a system bandwidth of 400 MHz.

The multipactor electron gun used to charge the material samples for these tests produces a beam that is uniform to within 10% over the entire area of the largest samples tested.

D. Discharge Characterization Test Results

Initial discharge characterization experiments were performed using samples of Teflon tape of a type commonly used for thermal control purposes on operational satellites. This material consists of a layer of 5-mil Teflon having a continuously-silvered back surface coated with a conductive adhesive.

The waveform shown in Figure 9 was obtained as a result of a discharge on a 4-in. x 9-in. Teflon tape sample mounted directly on the ground plane as shown in Figure 8. The distance from the nearest sample edge to the loop antenna was approximately 3 in.

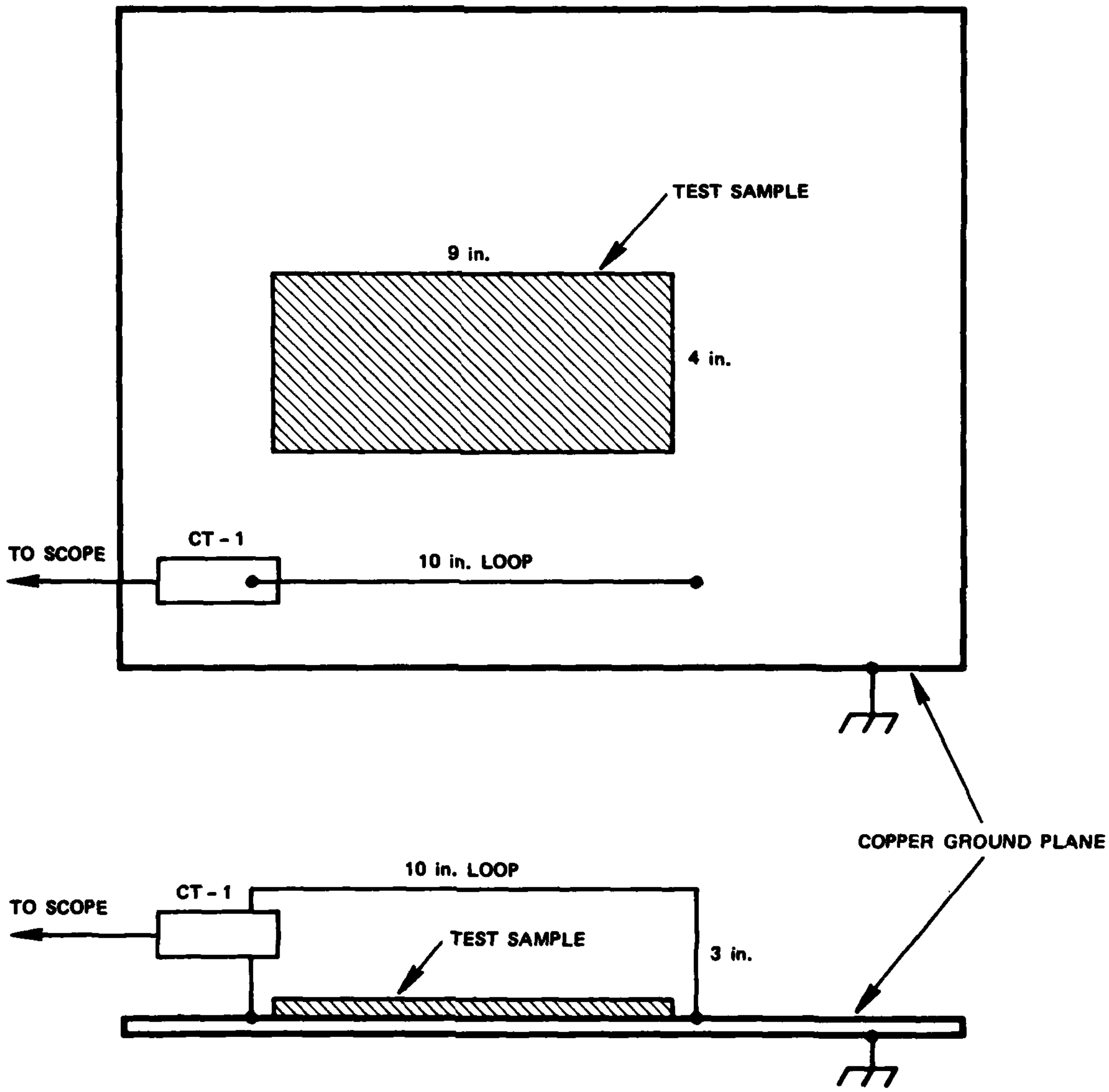
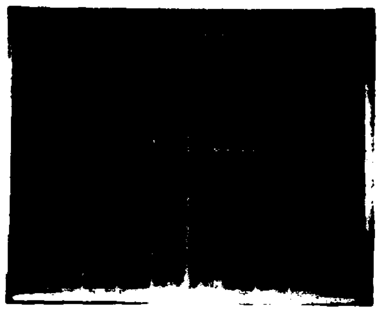


FIGURE 8 TEST SETUP FOR DISCHARGE CHARACTERIZATION

The 28.5-A amplitude of the current pulse shown in Figure 9 is typical of a number of the largest pulses observed on the 4-in. x 9-in. Teflon test sample. In general, the measured pulse amplitudes ranged from approximately 10 A to 30 A, all having waveshapes similar to that of Figure 9.

For a shorted half-loop antenna on a ground plane, the relationship between the propagating magnetic field (H) and the measured current (I) is given by $I = u_o A L^{-1} H$, where $u_o = 12.57(10^{-7})$ H/m and A and L are the area of the loop and the loop inductance, respectively. For the loop used in these tests, $A = 0.023\ m^2$ and $L = 365$ nH. The relationship between H and I is therefore given by $H = 12.6\ m^{-1}\ I$.



VERTICAL SCALE: 15.8 A/div.
HORIZONTAL SCALE: 100 nS/div.

FIGURE 9 CURRENT WAVEFORM, 4 - in. x 9 - in. SILVERED - TEFLON TAPE SAMPLE

The peak magnetic field of the transient pulse of Figure 9, shown on the right-hand axis, is therefore 360 A/m, and the range of measured H fields is from 126 to 378 A/m.

For a field propagating in free space, the ratio of the electric field (E) to the magnetic field (H) is 377 ohms. Although direct measurements of the transient electric field were not made for this program, an estimate of the electric-field amplitude can be made using this ratio. The result is an electric-field peak amplitude of 136 kV/m for the waveform of Figure 9 and a

typical range from 47 to 142 kV/m. These electric field estimates may be somewhat conservative since, in the test arrangement of Figure 8 with the magnetic-field sensor close to the source of the transient field, the actual ratio of E to H may be somewhat higher than 377 ohms.

The discharge resulting in the waveform of Figure 9 was produced with an electron-beam energy of 15 keV and a current density of 3 nA/cm^2.

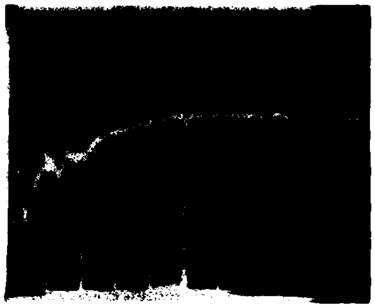
Several additional series of tests using silvered-Teflon samples were performed over a wider range of energies and current densities. As was expected, the rate of occurrence of discharges increased at higher beam current densities. However, there was no noticeable variation in the range of observed transients with beam current densities from 1 to 10 nA/cm^2 and at beam energies of 15 and 20 keV.

A similar series of tests was performed using an optical solar reflector (OSR) test panel in order to compare the results with those obtained from the Teflon tests. The OSR panel consists of an 8 by 6 array of one-in. square, 10-mil thick quartz second-surface mirrors bonded to a magnesium substrate by a thin layer of non-conductive RTV adhesive. This array was mounted directly on the ground plane with its longest edge parallel to and approximately 3 in. from the loop antenna.

A typical waveform obtained during the OSR tests is shown in Figure 10. The peak current measured in this pulse is 8.75 A corresponding to a magnetic field peak amplitude of 110 A/m. Use of the 377 ohm free-space E/H field ratio therefore yields an electric-field magnitude of 41.6 kV/m. The current waveform of Figure 10 had the highest amplitude of those measured during the OSR tests. The observed peak current amplitudes ranged from 5 to 8.75 A, corresponding to magnetic-field amplitudes of 63 to 110 A/m and to free-space electric-field amplitudes of 23.8 to 41.6 kV/m.

It can be seen from Figure 10 that the current waveform produced by the OSR test panel is somewhat more complex than those produced by the Teflon tape test samples. Visual observations of discharges on the OSR panel indicate that many individual discharges appear to occur simultaneously over a considerable portion of the panel. It is likely that a discharge on

one of the panel cells causes a field redistribution that triggers discharges on adjacent cells and that the complexity of the generated waveform is a result of this process.



VERTICAL SCALE: 2.5 A/div.
HORIZONTAL SCALE: 50 nS/div.

FIGURE 10 CURRENT WAVEFORM, 8-in. x 10-in. OSR PANEL

As was true of the Teflon sample tests, no great variations in the measured waveforms were observed as the electron beam current density and energy were varied over 1- to 10- nA/cm^2 and 15- to 20-keV ranges, respectively.

From an electromagnetic interference viewpoint, the magnitudes and time structures of the transient fields measured on both Teflon and OSR samples pose a potentially serious threat to spacecraft operation. The implications of the results of these tests are further discussed in Section III.

III SUMMARY AND CONCLUSIONS

A. Conclusions

In the experimental work performed on this program, the areas of dynamic material charging behavior and resulting electrical breakdowns have been explored relatively separately in an effort to establish baseline data in each area. The results of this work indicate that many present laboratory simulation and measurement techniques may not provide data truly representative of actual in-orbit spacecraft charging effects.

The results of the materials charging behavior studies provide an empirical understanding of some of the complexities of materials behavior under dynamic conditions more typical of those encountered in space than are normally used in ground-based simulations.

The observed differences in behavior between Kapton and Teflon materials under dynamic test conditions demonstrate that the effects of differential charging on operational space vehicles can be critically dependent upon the geometries and combinations of materials used for vehicle construction.

The discharge characterization studies performed on this program have provided fundamental information on the magnitudes and time structures of the actual external electromagnetic fields produced by materials discharges.

In many of these tests, electromagnetic transients caused by sample discharges produced signals in external sensors indicative of transient electric-field changes of tens of kV/m at locations several inches from the sample boundaries. The magnitudes of these external fields are comparable to those associated with nuclear electromagnetic pulse (EMP) events and can produce high-level transient signals in spacecraft electronic systems. These transient electromagnetic signals can therefore be considered as extremely energetic sources of possible electromagnetic interference on spacecraft.

Of all presently known spacecraft charging phenomena, electrical discharges are the most potentially dangerous threat to the operational lifetimes of space systems but, at present, the physics of the discharge process is poorly and inadequately understood.

B. Recommendations

Sample bulk-current and potential measurements are being made by the Sample Surface Potential Monitor (SSPM) experiment on board the 1-rpm spin rate P78-2 SCATHA Satellite for Kapton, Teflon, and other materials. Based upon the results of the laboratory tests performed for this program, it is expected that similar complexities in materials behavior will be observed during the SSPM experiment in space.

A comparison of the results of the laboratory simulation tests described herein and of related tests performed by other agencies with the in-orbit SSPM data would allow the adequacy of present ground-based materials test techniques to be assessed. This information is required to allow the development and improvement of laboratory simulation techniques to accurately predict the behavior of both single materials and complex combinations of materials in space. This information will also aid in the development of new materials and systems for satisfactory or improved performance on future space vehicles.

This work should be facilitated by data obtained from the P78-2 vehicle which will provide a better model of the actual dynamic in-orbit charged particle environment and therefore allow requirements for ground-based simulation to be more clearly defined.

In this regard, preliminary work is currently under way at SRI International on a concept for the modification of the multipactor electron source to provide a large-area electron beam having a continuous, wide-range energy spectrum more typical of that encountered in the actual space environment. If this development work proceeds as planned, an electron source having a tailorable energy spectrum should become available for use in laboratory simulation studies in the near future.

Further analytical and laboraory efforts, as well as in-flight measurements, are also needed to provide a better quantitative understand ing of dynamic current flow and charge storage mechanisms in spacecraft dielectrics over the operational range of charged-particle and solar-illumination environments. This could ultimately lead to the use of more cost-effective analytical modeling techniques for the prediction of materials behavior in space and the development of new materials.

Partially as a result of the significance of the electrical discharge information obtained during this program, an additional program for more precise characterization of the electromagnetic signals generated by electrical breakdown of spacecraft materials was initiated under Air Force SAMSO sponsorship.

As part of this program, a separate series of "quick-look" laboratory tests are being performed by SRI International in a special electromagnetic test setup. This test facility is designed to provide a clearly defined, electromagnetically "clean" environment in order that the data obtained be free of artifacts associated with the test setup. In addition, specially designed wide-band, high-performance sensors and signal processing electronics are being used for these tests.

A major reason for the performance of these "quick-look" measurements is to provide preliminary information on the source characteristics of spacecraft discharges in a form suitable for use in electromagnetic compatibility studies.

Due to time and funding contraints, work on the SAMSO program is presently confined to the assembly and checkout of the test facility and to the performance of a limited number of measurements on a few test samples. This preliminary work has been completed over the past few months[7]. The data obtained is being analyzed and a report is currently in preparation.

Although limited in number, the results obtained in these tests more accurately confirm the magnitudes of the electric field changes inferred in Section II D and provide considerable additional detail regarding the time structure of the fields produced by discharge events.

An understanding of the characteristics of external electromagnetic field transients produced by electrical breakdown of spacecraft dielectrics is necessary for the accurate assessment of the electromagnetic interference threat to specific spacecraft systems and for the specification of requirements for weight- and cost-effective shielding techniques and system immunity to upset or damage.

The overall plan for the follow-on to the SAMSO program is intended to provide, as completely as possible, a characterization of the electromagnetic properties of electrical breakdowns on spacecraft materials in a form suitable for use in EMI studies and analyses, an understanding of breakdown initiation and propagation mechanisms for inclusion in analytical breakdown models and for the guidance of materials selection and development for future space systems, and empirical data for comparison to, and verification of, the results of analytical modeling efforts.

In addition, it is strongly recommended that plans be made for the performance of accurate in-orbit discharge characterization measurements to confirm the adequacy of these analytical and laboratory simulation efforts.

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